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Repetitive control of an *XYZ* piezo-stage for faster nano-scanning: Numerical simulations and experiments

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ABSTRACT

A repetitive controller (RC) is implemented to control the *Z*-axis movements of a piezo-scanner used for AFM scanning and then tested through scan experiments and numerical simulations. The experimental and simulation results show that the RC compensates phase delays better than the standard PI controller at high scan speeds, which leads to less scan error and lower interaction forces between the scanning probe and the surface being scanned. Since the AFM experiments are not perfectly repeatable in the physical world, the optimum phase compensators of the RC resulting this performance are determined through the numerical simulations performed in MATLAB/Simulink. Furthermore, the numerical simulations are also performed to show that the proposed RC is robust and does not require re-tuning of these compensators when the consecutive scan lines are not similar and a change occurs in the probe characteristics.

1. Introduction

Increasing the scan speed of an AFM without sacrificing the scan quality is an active area of research. One method of increasing the scan speed of an AFM is by improving the mechanical design of the scanner. In this context, the goal is to increase the resonance frequency of the scanner so that the scanner has a larger bandwidth, allowing higher speeds to be achieved. For this purpose, a two-layered scanner architecture is proposed in [1], which guarantees decoupling of the *X* and *Y* axes and provides faster *Z*-axis motion. A fast scanner is designed in [2] by pushing the performance of each individual part of electronics to its limit: a preamplifier with a bandwidth of 600 kHz, a feedback electronics with a bandwidth of 1 MHz, a home-built bus structure for fast data transfer, fast analog to digital converters, and low-noise drivers. The scanner proposed in [3] can achieve scanning speeds that are more than two orders of magnitude faster than the current commercial AFM systems. The new design is based on piezoelectric stack actuators and a flexure mechanism that enables decoupling of the different axes of motion while keeping the mechanical structure stiff. Moreover, in order to reach high resonance frequencies (and hence high scan speeds) in all positioning directions, the mechanical paths are kept as short as possible. In [4], a high resonance frequency of 540 kHz is achieved for the *Z*-actuator using a support mechanism, what the authors call as "inertia balance". In this method, a cubic piezo actuator enabling the *Z*-motion is supported at the four sides perpendicular to the extension axis to increase its resonance frequency.

The other method for increasing the scan speed of an AFM is to replace the conventional PI controller used in the feedback loop with a more sophisticated one (see the review of the control literature in [5–7]). In this study, we focus on the latter method and propose a repetitive controller (RC) for faster scanning of nano-scale surfaces in tapping mode AFM. The existing control studies on AFM can be categorized into two groups: (a) those aiming to control the scanning probe and (b) those focusing on the control of the scanner (i.e. the piezo actuator holding the sample). The latter group can be further divided into two sub-groups: controllers designed to improve the scan speed by adjusting the periodic lateral movements of the scanner on *X*–*Y* plane and those designed to maintain the image quality at high scan speeds by adjusting the vertical movements of the scanner along the *Z*-axis. In Fig. 1, the movements of the scanner along the *X*, *Y* and *Z* axes during an AFM scan are illustrated. Typically, the scanner is moved back and forth on the *X*-axis by sending a triangular voltage signal to the *X*-actuator while it is slowly advanced along the *Y* axis by sending a ramp voltage signal to the *Y*-actuator. The resulting scan motion is a triangular trajectory on the *X*–*Y* plane. Obviously, tracking a periodic back and forth motion is more challenging than tracking a ramp input. Hence, the research in that area is mostly focused on

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